

PATENT SPECIFICATION

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DRAWINGS ATTACHED

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(54) VARIABLE PULSE LASER

(71) We, SANDERS ASSOCIATES, INC., a Corporation organized and existing under the laws of the State of Delaware, United States of America, of Daniel Webster Highway, South, Nashua, New Hampshire, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to lasers. More particularly the invention relates to solid state lasers.

In the prior art solid state lasers of the conventional type utilize typically a xenon flashlamp as an optical pump and a ruby or neodymium glass rod as an emissive element oriented along an optical path between reflecting surfaces of a Fabry-Perot cavity.

For Q-switching, one of the reflecting surfaces may be rotated to inhibit lasing until a desired threshold is obtained. Another device used for Q-switching is a dye solution which bleaches out above a selected radiation intensity and becomes transparent to permit lasing at that level.

The peak power at which such devices can operate is limited in the first instance to a level below which the emissive rod operates coolly and without shattering. Characteristically such lasers are discontinuous in operation and the pump operates at selected intervals, i.e. the laser is pulsed.

In the prior art Q-switched lasers, the pulse of radiation is limited in length to from 10 to 200 nanoseconds. The flash which precipitates the pulse extends in duration for approximately 100—4000 microseconds. The pulse length of a given prior art Q-switching type laser is not variable.

In a preferred embodiment of the invention a pulse laser is provided having an output pulse whose amplitude shape and duration can be variably controlled. The

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laser may be a solid state laser which generates multiple pulses upon the injection of a single pulse of enabling energy.

According to the present invention there is provided a laser including a source of enabling energy, a resonant cavity including Q-switching means, an active laser medium disposed within the resonant cavity and responsive to the enabling energy for producing pulses of plane polarised radiation along a path including the laser medium, a non-linear absorption means intercepting the said path for controlling the peak intensity of the radiation to a selected maximum level and means for varying the amplitude shape and duration of the radiation pulses.

In one form of the invention the source of enabling energy is an optical pump. The stimulated emission means is a transparent medium formed of a material susceptible of stimulated emission and the cavity means includes a pair of optical reflecting surfaces for reflecting light energy successively through the medium.

In another form of the invention the element is formed of a material which generates a harmonic frequency of the radiation and absorbs the harmonic frequency radiation.

In still another form of the invention the element is adjustable to vary the crystallographic orientation with respect to the light energy from the laser to vary the degree and character of absorption. Here the element is formed of a single crystal material having a selected crystallographic orientation.

In another form of the invention a second amplifier comprising a transparent stimulated emission medium is oriented along the optical path and the optical pumping means provide enabling energy in common for the first and second stimulated emission means.

An embodiment of the invention, together with embodiments to which the invention can be applied, will now be described.

cribed with reference to the accompanying drawings in which:

Fig. 1 is a schematic diagram of a laser to which the invention can be applied,

5 Fig. 2 is a schematic diagram of a modification of the laser shown in Fig. 1,

Figs. 3(a) to 3(e) are graphs of a series of curves illustrating the operation of the lasers of Figs. 1 and 2,

10 Fig. 4 is a schematic diagram of another modification of the laser shown in Fig. 1,

Fig. 5 is a schematic illustration of an embodiment of the present invention, and

15 Figs. 6A to 6C are graphs of the variable pulses achievable through the practice of the present invention.

Referring now to the drawings and with particular reference to Fig. 1, there is here illustrated a schematic diagram of a laser apparatus. While the following description is taken with respect to a laser, it will be apparent that the principles are applicable for all electromagnetic frequencies wherein stimulated emission is possible. As is well known in the art, the limiting factor on the frequency of operation is the relaxation time associated with the excited states of the emissive material.

20 Thus, we have here illustrated a laser generally indicated at 10 having an emissive rod 11 which is inherently capable of stimulated emission. The rod 11 may be formed, for example, of ruby or neodymium glass. An optical pump 12 such as a xenon flash-lamp provides the enabling energy for causing the rod 11 to produce stimulated emission radiation along an optical path 13 including the rod 11. A cylindrical reflector, not shown, surrounds the lamp 12 and rod 11. The rod 11 is disposed along the optical path 13 in a Fabry-Perot cavity between the reflecting surfaces provided by a prism 14 and a semi-transparent reflector 15. An element 16 for restricting the peak intensity of said radiation to a selected maximum level is disposed between the rod 11 and the reflecting surface of the prism 14. The restricting element 16 is a non-linear absorption device which increases its absorption rate as the intensity increases tending to hold down the intensity of any given ray. The response time of a control element of this character is less than the duration of the radiation pulses from the laser. Normally, lasing actions tend to take place in the rod in a filamentary fashion so that the resultant beam at the surfaces of the rod consists of a plurality of point sources of light or infrared energy. The term "optical" or "light" as used herein includes, but is not limited to, all wavelengths of light including infrared and ultraviolet. The prism 14 is shown rotatable Q-switching purposes to develop a higher threshold of operation 65 for the beam.

The control element 16 may be formed, for example, of a photoconductive material such as cadmium sulfide which exhibits the property of non linear absorption, i.e. absorption increases as the intensity increases. The term "second harmonic" as used here includes the so-called two photon absorption effect. The instantaneous appearance of two photons cannot be distinguished from the second harmonics. A discussion of second harmonic generation and two photon absorption may be found in an article entitled "Non Linear Optics" by R. W. Minck, R. W. Terhune and C. C. Wang in Applied Optics, October, 1966, pages 1595-1612. Note particularly Figs. 7-10 on pages 1603 and 1604. Thus, any tendency for the laser to produce sharp intense peaks along a filament is eliminated, thereby protecting the rod from hot spots and overheating and consequently, shattering. It is deemed feasible to form the rod 11 of a material which exhibits stimulated emission and which also absorbs energy in a manner required to maintain the intensity of the energy at a reduced level. For cadmium sulfide, the element 16 is oriented at a Brewster angle of approximately 70° to avoid introducing additional Fabry-Perot reflection surfaces to reduce losses in the optical cavity. The Brewster angle is chosen because the light coming from the rod 11 is plane polarized.

Note that the reflector 15 may itself be a Fabry-Perot cavity. The reflecting surfaces 15a and 15b provide the cavity and the energy is internally reflected therebetween.

The theory of the operation of the laser is well known in the art and well described in the literature particularly in the context of a Fabry-Perot cavity. More particularly, the theory of such a laser is outlined in United States Patent No. 2,929,922 issued to Townes and Schlawlow. The prism 14 is shown rotatable to enable Q-switching and thus to increase the peak power output in the well known manner. The lamp 12 may, for example, be a xenon lamp, the intensity of which is a function of the voltage applied to the lamp. By varying the voltage to the lamp, the intensity may be varied. In the present laser this results in varying the length of the output pulses from 10 nanoseconds to over 2000 nanoseconds. A variable voltage source 17 is shown coupled to the lamp 12.

In an apparatus built and tested a model No. 1009 laser as manufactured by Applied Lasers, Inc. of Stoneham, Massachusetts was modified to include a restricting element in the position indicated in Fig. 1. A ruby rod 3" long by $\frac{1}{4}$ " diameter was used. The Brewster angle chosen was approximately 70°. The restricting element was formed of cadmium sulfide in an elliptical disc of approximately 18mm × 50mm

shaped as shown in Fig. 1. The thickness of the control element determines the degree of absorption which takes place. In the sample tested, the thickness was approximately 5mm. The cadmium sulfide was a single crystal of excellent optical quality. The faces were fabricated parallel to within two (2) seconds of arc. The crystallographic C axis was oriented along the major axis of the ellipse.

A typical frequency of operation is 6943Å. In the apparatus tested the input energy was 800—1600 joules and the peak output power was approximately 10^6 watts.

Referring now to Fig. 2 there is here illustrated an oscillator amplifier laser capable of producing high output powers for extremely long pulse duration, e.g., over 2 microseconds. Here the same flash lamp is used to stimulate emission both in the oscillator portion of the laser and the amplifier portion of the laser. Thus, referring now to Fig. 2 an oscillator emissive rod 20 is disposed between a semi-transparent reflector 21 and a Q-switching reflecting prism 22. A pair of flashlamps 23 and 24 illuminate both the oscillator rod and an amplifier rod 25 formed of material exhibiting stimulated emission. A reflector 26 surrounds both rods 20 and 25 and is used to optically pump both rods simultaneously. The rod 25 is preferably fashioned of a longer piece of material and larger in diameter to provide a higher power output. Again, a restricting element 27 is shown disposed between the rod 20 and the reflecting surface of the prism 22. The prism 22 is rotatable as described above for Q-switching purposes.

In the prior art oscillator amplifier, if the same optical pump were used for both rods, the oscillator rod would shatter. Here, however, the pulse length is increased and higher oscillator energies are obtained. The maximum power within the oscillator rod is substantially controlled by the non linear element rather than by the flashlamp intensity.

The laser of the present invention provides a laser having many advantages. More particularly, the average power in time is increased. The average power possible across the cross-section of the rod is increased. The pumping power possible is increased and the overall efficiency of the laser is increased.

By reducing the peak pulses along a filament by using the restricting element in the manner of the present invention, the average power of a Q-switched laser may be substantially increased. A further advantage is that the laser will more readily operate under degraded conditions. For example, Q-switching takes place over a much wider range from for example, 300 to 1300 micro-

seconds after the light flash. For a prior art apparatus the Q-switching time for the same light flash conditions must be within 500—550 microseconds. Further by virtue of the ability to increase the pumping energy varying pulse lengths may be obtained with substantially constant amplitude by varying the pumping power.

Referring now to Fig. 3, there is here illustrated a series of curves relating to the operation of a laser to which the invention may be applied. When a ruby rod is stimulated by enabling energy, such as xenon flashlamp, it tends to lase in a filamentary fashion. Given a flash of the characteristic shown by the solid line curve in Fig. 3(a) the radiation intensity varies across the cross-section of the rod as shown, for example, in the curve (b) of Fig. 3. Since a hot spot occurring in a relatively small local area along a peak filament, for example, one (1) mm² can cause the rod to shatter, the peak intensity of the enabling energy is limited to that described by the peak lasing action which takes place along a given filament. By restricting lasing along a given filament to a selected level, the intensity of the enabling energy may be increased, thereby increasing the intensity of lasing throughout the cross-section of the rod as shown in the curve (c) of Fig. 3.

The resultant laser radiation intensity plotted against time in nanoseconds is shown in the curve (d) of Fig. 3. It is apparent that the peak intensity of the unrestricted curve is below that of the restricted curve and that the pulse length has essentially been stretched from, for example, 100 nanoseconds to 400 nanoseconds in duration. The curve indicative of the restricted case corresponds with the intensity as illustrated by the alternately broken line in the curve (a). The curve (e) of Fig. 3 corresponds with the intensity illustrated by the dashed line in the curve (a). The curve (e) further illustrates the generation of multiple pulses with a single flash of enabling energy.

Referring now to Fig. 4, there is here illustrated a modification of the laser in Fig. 1. Here like reference numerals correspond with like parts in Fig. 1.

Here an optical transformer has been added to increase the intensity at the element 16. The transformer includes a condensing lens 30 and collimating lens 31 to concentrate the energy on the element 16. In this manner an element with a given threshold controlling action may be used with a wide range of energies. Threshold control may be provided from below one (1) watt per cm² to over 10^{18} watts per cm². The transformer may be reversed to use a divergent lens system which reduces the

intensity of radiation at the control element.

It has been found by the Applicants that the output radiation pulses of a Q-switched laser fabricated in accordance with the principles of the present invention may be readily controlled as to amplitude, shape and duration. As the laser is applied to various practical manufacturing problems particularly in the field of micro-electronics it becomes apparent that the laser pulse requirements for one operation such as drilling are different from those for another operation such as welding. It has thus become highly desirable to provide a pulsed laser having a controllable output.

With reference to Figure 5 there is illustrated an embodiment of the present invention whereby the laser output pulse shape may be precisely controlled. The active laser element 40 is pumped with energy from a flashlamp 42 which is coupled to a variable voltage supply 44. The resonant cavity is defined by a reflector 46 preferably of the dielectric interference type and a Pockels cell 48 with its associated switching circuitry 50 and mirror 51. The Pockels cell 48 is provided with a variable RC circuit 52 whereby the turn-on time of the Pockels cell may be varied from its normal value of about 5 nanoseconds to hundreds of microseconds. The non-linear absorption crystal 54 is provided with a worm and gear assembly 56 such that the crystal 54 may be rotated in its own plane.

The radiation 58 emitted by the active laser rod 40 is polarized by the Brewster windows 60 in which the rod ends are formed. When the crystallographic c-axis of the absorption crystal 54 is oriented parallel to the polarization of the radiation from the rod 40 the laser output pulse is characterised by a sharp intensity rise to a maximum value and a relatively long tail of decreasing amplitude as illustrated in Figure 6A. As the c-axis of the crystal 54 is rotated in its own plane out of coincidence with the direction of polarisation the non linear losses within the crystal are changed, the peak pulse amplitude is decreased and the tail or duration of the pulse is increased. Alternatively the direction of polarisation of the laser radiation may be rotated by known techniques and the crystal maintained stationary.

Curves 6B and 6C illustrate this effect and represent radiation pulses obtained by the Applicants with relative rotation of the crystallographic axis of the crystal and radiation polarization of 10 degrees and 45 degrees respectively. It has further been found by the Applicant that when the turn-on time of the Pockels cell 48 is increased by adjusting the RC circuit 52 the length of the laser output pulse is correspondingly

increased. As discussed hereinabove the pulse length may also be varied through adjustment of the voltage from source 44 applied to the flashlamp 42.

Thus it will be seen that the output pulses of a laser fabricated in accordance with the present invention may be controlled in three ways: by varying the flashlamp voltage, by providing relative rotation of the non-linear absorption crystal and the radiation polarization and by varying the turn-on time of the Pockels cell Q-switch. The Applicants thus provide a pulsed laser the output of which is both smoothed and controllably variable as to pulse amplitude, shape and duration over a wide range. A single laser may thus be applied to a variety of industrial problems such as drilling, welding and cutting.

It may thus be seen that it is possible to provide, in accordance with the invention, a solid state laser having a non-linear absorption element inserted in the optical path between the emissive rod and a reflecting surface of the Fabry-Perot cavity. The absorption element is preferably transparent to radiation at the fundamental frequency below a selected threshold. Above the threshold the element increases its absorption as the intensity of the radiation at the fundamental frequency increases. The amplitude, shape and duration of the laser output pulses are controllably variable through adjustment of the pump intensity, rotation of the non linear absorption element and variation of the turn-on time of the laser Q-switch.

WHAT WE CLAIM IS:—

1. A laser including a source of enabling energy, a resonant cavity including Q-switch means, an active laser medium disposed within the resonant cavity and responsive to the enabling energy for producing pulses of plane polarised radiation along a path including the laser medium, a non-linear absorption means intercepting the said path for controlling the peak intensity of the radiation to a selected maximum level and means for varying the amplitude shape and duration of the radiation pulses.

2. A laser as claimed in claim 1 wherein the means for varying the amplitude and duration of the radiation pulses includes means for adjusting the position of the non-linear absorption means thereby to adjust the degree of absorption.

3. A laser as claimed in either claim 1 or claim 2 wherein the means for varying the amplitude shape and duration of the radiation pulse includes means for providing relative rotation between non-linear absorption means and the polarization of the radiation.

4. A laser as claimed in claim 1 wherein

the Q-switching means is a Pockels cell and the means for varying the amplitude shape and duration of the radiation pulses include means for varying the turn-on time of the Pockels cell.

5 5. A laser as claimed in any one of the preceding claims wherein the non-linear absorption means is a single crystal having a selected crystallographic orientation and
10 plane parallel faces, disposed with the said faces oriented at Brewster's angle relative to the said radiation path.

15 6. A laser as claimed in any one of the preceding claims wherein the non-linear absorption means is formed of a material which generates a harmonic frequency of the said radiation and absorbs the harmonic frequency radiation.

20 7. A laser as claimed in any one of the preceding claims wherein the non-linear absorption means is a photoconductive material.

25 8. A laser as claimed in any one of the preceding claims wherein the active laser medium is ruby and the non-linear

absorption means is a single crystal of cadmium sulfide.

9. Apparatus as claimed in any one of the preceding claims including a second active laser medium disposed in the said
30 path for receiving enabling energy from the source of enabling energy.

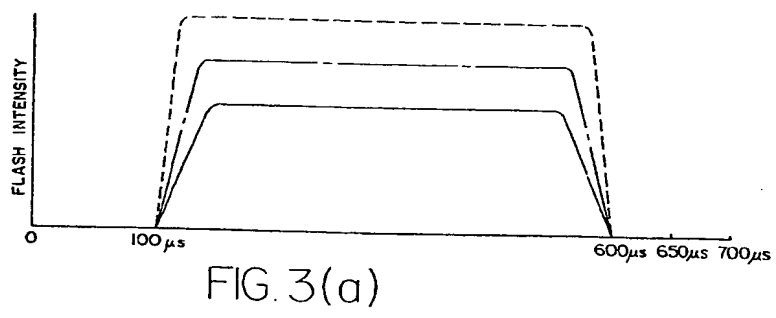
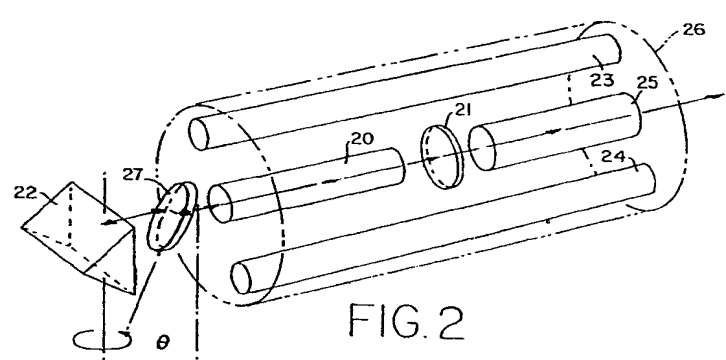
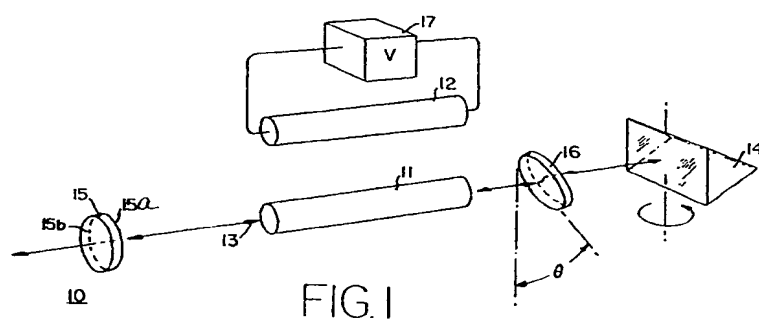
10. Apparatus as claimed in any one of the preceding claims including an optical transformer disposed in the path between
35 the non-linear absorption means and the active laser medium.

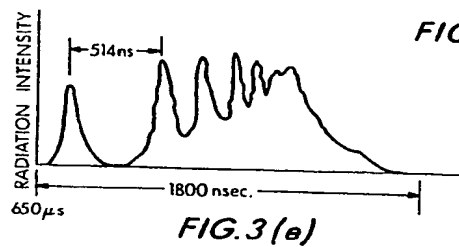
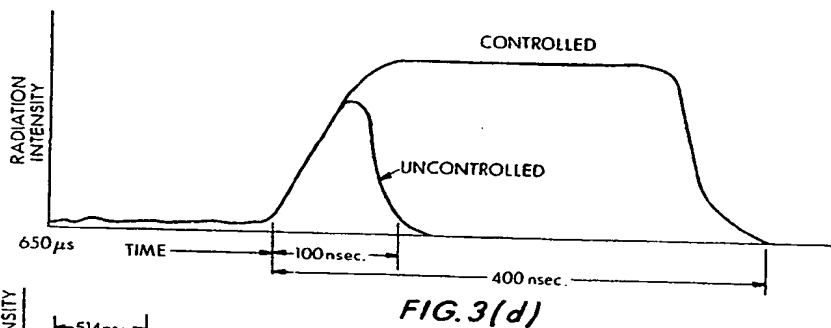
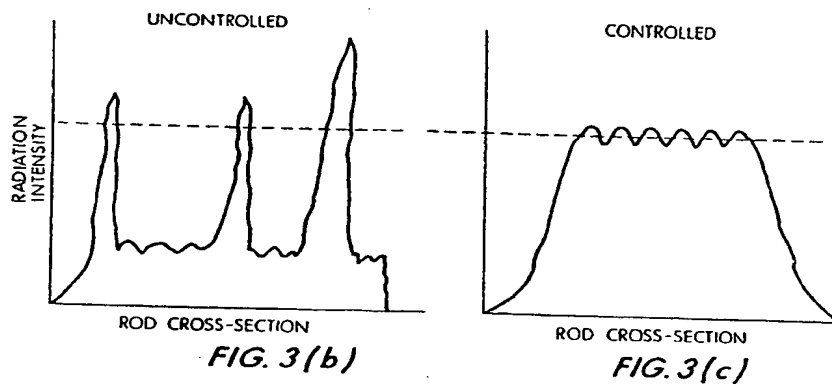
11. A laser substantially as described with reference to Fig. 5 of the accompanying drawings.
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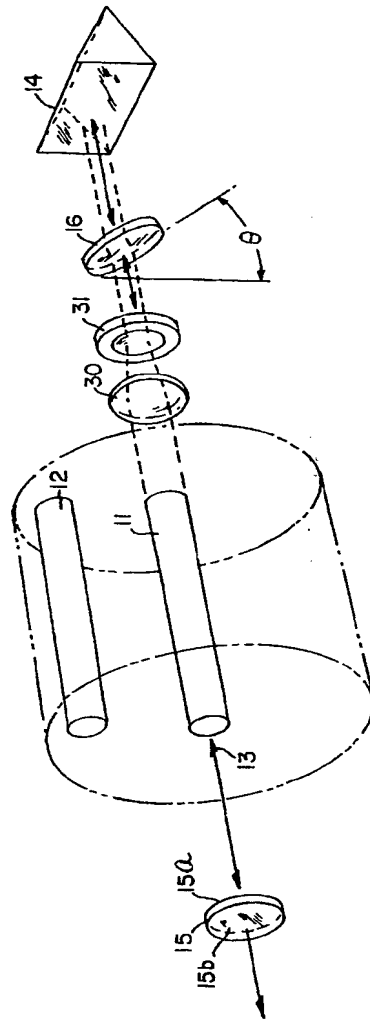
12. A laser as claimed in any one of the preceding claims when operated substantially as described with reference to Figs. 6A to 6C of the accompanying drawings.

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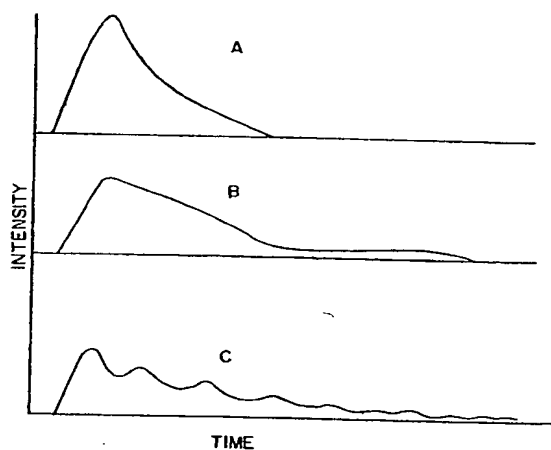
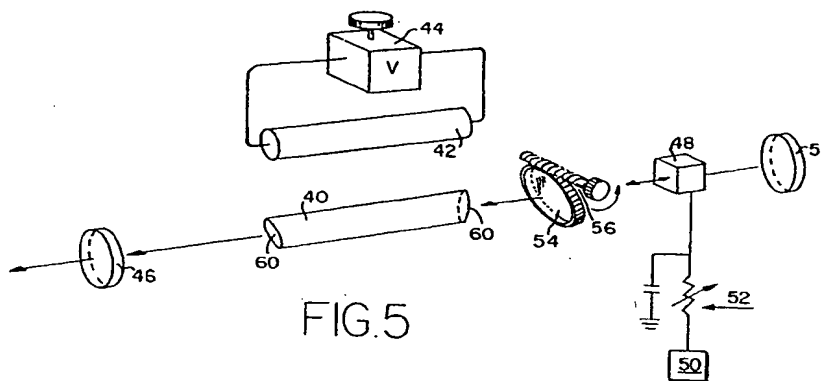
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COMPLETE SPECIFICATION

4 SHEETS

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the Original on a reduced scale*

Sheet 4



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